CO_2 INJECTION IN DEEP SALINE SLOPING AQUIFERS THROUGH A VERTICAL WELL

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INTRODUCTION

Anthropogenic CO_2 emissions are expected to continue to increase worldwide in the next decades. This could dramatically increase CO_2 concentrations in the atmosphere. One potential mitigation action is CO_2 permanent storage in deep saline aquifers. CO_2 is injected as a supercritical fluid (temperature and pressure higher than 31.1 ºC and 7.38 MPa, respectively) so as to obtain a relatively high density that minimizes the volume occupied by this greenhouse gas. CO_2 density is highly dependent on temperature and pressure because of its high compressibility (Vilarrasa *et al.*, 2010a), adopting a wide range of values (450-800 kg/m^3). Since CO_2 is lighter than brine, flow is affected by buoyancy.

Buoyancy produces an upslope migration of the CO_2 bubble in sloping aquifers. The post-injection fate of CO_2 in sloping aquifers has been investigated (e.g. Hesse *et al.*, 2008; Elenius *et al.*, 2010) but without considering the actual shape of the CO_2 bubble at the end of injection. However, the shape of the CO_2 bubble at the end of injection affects its posterior evolution (McMinn & Juanes, 2009). Gasda *et al.* (2008) studied the effect of a slope up to 1º during the injection period using a 2D model, which represents injection through a horizontal well. However, CO_2 injection through a vertical well, which implies a 3D geometry, has not yet been investigated.

CO_2 will be injected in the Hontomín CO_2 pilot storage site, Burgos (Spain). Hontomín is the site for the CO_2 storage Technology Demonstration Plant (TDP) of the Compostilla OXYCFB300 project, operated by Energy City Foundation (CIUDEN). CO_2 will be injected through a vertical well in a flank of a dome-like structure with a slope close to 20º at a depth around 1450 m. CO_2 injection tests are aimed to gain knowledge on trapping mechanisms and CO_2 bubble and pressure evolution. Pressure evolution is important for assessing the caprock integrity and to avoid the open up of preferential paths for CO_2 leakage (Vilarrasa *et al.*, 2010b, 2011). These processes are relatively well known in horizontal aquifers, but a high uncertainty still exists in sloping aquifers.

IMPLEMENTATION OF CO_2 MODULE IN CODE_BRIGHT

CODE_BRIGHT has been adapted to simulate CO_2 injection. To do so, an equation of state for CO_2 has been implemented. CO_2 density follows a Redlich-Kwong equation of state type with the parameters proposed by Spycher *et al.* (2003). CO_2 viscosity has been taken from Altunin & Sakhabetdinov (1972). These expressions for CO_2 density and viscosity are valid regardless of the temperature and pressure conditions (Figure 1).

Additionally, water density increase due to CO_2 dissolution has been implemented following Garcia (2003).

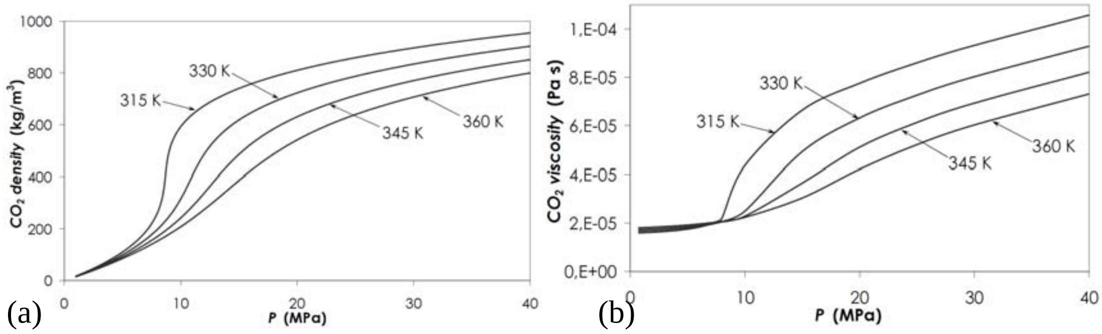

Figure 1. (a) CO_2 density and (b) viscosity as a function of pressure for several temperatures.

MODEL SETUP

To model CO_2 injection in a sloping homogeneous aquifer, we use a 3D model. Since we are interested in simulating CO_2 injection tests of 100 t of CO_2 during 1 week, we model half of the domain, 200x70x10 m^3, by making use of the symmetry in the direction of maximum slope. The upslope and downslope boundaries are treated as constant head boundaries. The aquifer permeability is 10^{-13} m^2 and its porosity 0.1. The slope of the aquifer ranges from 0º to 20º. The mesh is structured, made of hexahedrons of 1 m in side. We use the finite element numerical code CODE_BRIGHT (Olivella *et al*., 1994, 1996) modified for CO_2 injection.

GRAVITY NUMBER

Consider the injection of compressible CO_2 in a deep homogeneous horizontal confined brine aquifer through a vertical well. Mass conservation of these two fluids can be expressed as (Bear, 1972)

$$\frac{\partial(\phi S_\alpha \rho_\alpha)}{\partial t} + \nabla \cdot (\rho_\alpha \mathbf{q}_\alpha) = 0\,, \qquad (1)$$

where ϕ is porosity, t is time, S_α is the saturation of the α -phase, ρ_α its density, $\mathbf{q}_\alpha$ its volumetric flux and α is either w brine or c CO_2. Momentum conservation is expressed using Darcy's law

$$\mathbf{q}_\alpha = -\frac{k k_\alpha}{\mu_\alpha}\left(\nabla p_\alpha + \rho_\alpha g \nabla z\right), \qquad (2)$$

where k is intrinsic permeability, k_α is relative permeability of the α -phase, μ_α its viscosity, p_α its pressure, g is gravity and z the vertical coordinate.

To quantify the relative influence of buoyancy we define a gravity number, *N*, as the ratio of gravity to viscous forces. We use the definition of Vilarrasa *et al*. (2010a) but adopted for sloping aquifers

$$N = \frac{2\pi r_{ch} b k \Delta\rho g \sin\theta \rho_{ch}}{\mu_c Q_m}\,, \qquad (3)$$

where b is the aquifer thickness, $\Delta\rho$ is the difference between the fluids density, θ is the slope of the aquifer, Q_m is the mass flow rate and the subindex *ch* denotes a characteristic variable.

NUMERICAL SIMULATIONS

We model the injection of CO_2 in a sloping aquifer through a vertical well. This enables to simulate a realistic evolution of the CO_2 bubble, which starts to advance through the top of the aquifer at the beginning of injection due to buoyancy (Figure 2). The CO_2 bubble advances both laterally and downwards as CO_2 pressure increases. The thickness of the aquifer that gets desaturated depends mainly on the aquifer transmissivity and CO_2 flow rate. Once CO_2 injection stops, the CO_2 bubble is displaced upwards due to buoyancy (Figure 2). This produces the migration of the CO_2 bubble through the top of the aquifer. This might be problematic if solubility and capillary trapping do not completely trap the CO_2 in free phase before it reaches a spillpoint (Gasda *et al.*, 2008; Elenius *et al.*, 2010). The length that the CO_2 will reach depends on the gravity number.

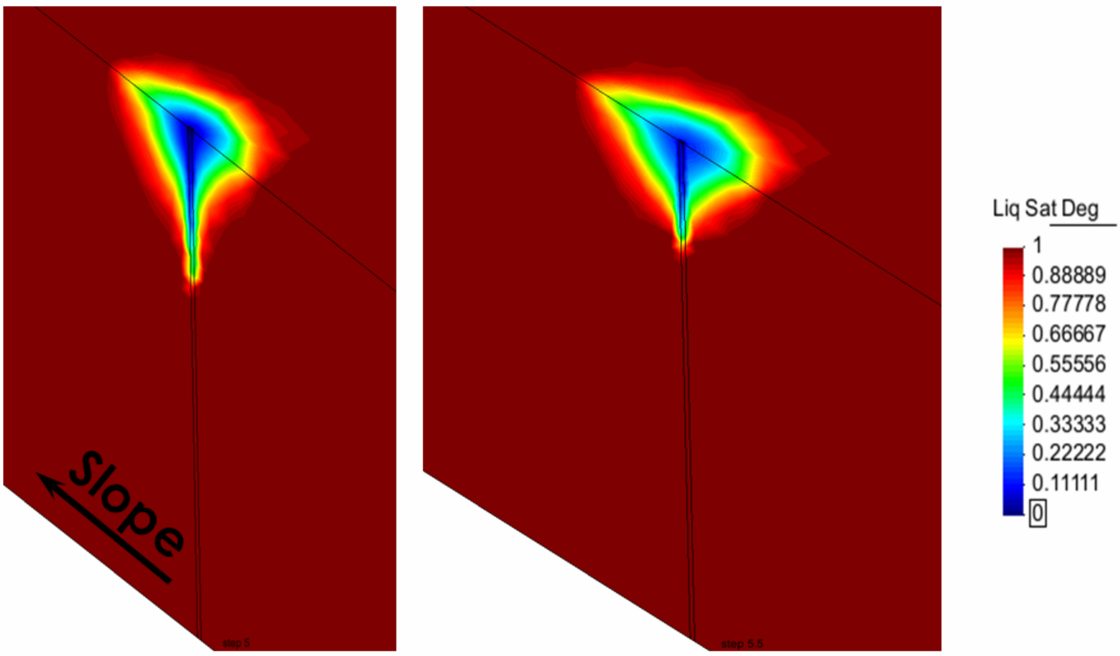

Figure 2. CO_2 bubble after 4 days of a 1 kg/s injection (left) and 0.5 days after injection stops (right). Note that the CO_2 bubble does not occupy the whole thickness of the aquifer (100 m thick). Note also that the CO_2 bubble is displaced upwards and dispersed laterally due to buoyancy once injection stops, advancing preferentially upslope.

CONCLUSIONS

CODE_BRIGHT has been successfully modified to simulate CO_2 injection in deep saline aquifers. The implemented density and viscosity functions are general and cover the whole range of depths and geothermal gradients of potential aquifers. CO_2 injection in sloping aquifers has been simulated using a 3D geometry.

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REFERENCES

Altunin, VV & Sakhabetdinov, MA (1972). Viscosity of liquid and gaseous carbon dioxide at temperatures 220-1300 K and pressure up to 1200 bar. *Teploenergetika*, 8:85-89.

Bear, J (ed.) (1972). Dynamics of fluids in porous media. Elsevier, New York.

Elenius, MT, Tchelepi, HA & Johannsen, K (2010). CO_2 trapping in sloping aquifers: high resolution numerical simulations. *XVIII International Conference on Computational Methods in Water Resources*, Barcelona.

Garcia, J.E. (2003). Fluid Dynamics of Carbon Dioxide Disposal into Saline Aquifers. PhD thesis, University of California, Berkeley.

Gasda, SE, Celia, MA & Nordbotten, JM (2008). Upslope plume migration and implications for geologic CO_2 sequestration in deep, saline aquifers. *The IES Journal Part A: Civil & Structural Engineering*, 1(1):2–16.

Hesse MA, Tchelepi HA & Orr FM Jr (2008). Gravity currents with residual trapping. *J. Fluid Mechanichs*, 611:35-60.

MacMinn CW & Juanes R (2009). Post-injection spreading and trapping of CO_2 in saline aquifers: impact of the bubble shape at the end of injection. *Compututational Geoscience*, 13:483-491.

Olivella, S, Carrera, J, Gens, A & Alonso EE, (1994). Non-isothermal multiphase flow of brine and gas through saline media. *Transp. Porous Media*, 15:271–93.

Olivella, S, Gens, A, Carrera, J & Alonso EE, (1996). Numerical formulation for a simulator (CODE_BRIGHT) for the coupled analysis of saline media. *Eng. Computations*, 13:87–112.

Spycher, N, Pruess, K & Ennis-king, J (2003). CO_2-H_2O Mixtures in the Geological Sequestration of CO_2. I. Assessment and calculation of mutual solubilities from 12 to 100°C and up to 600 bar. *Geochim. Cosmochim. Acta*, 67:3015-3031.

Vilarrasa, V, Bolster, D, Dentz, M, Olivella, S & Carrera, J, (2010a). Effects of CO_2 Compressibility on CO_2 Storage in Deep Saline Aquifers. *Transp. Porous Media*, 85(2):619-639.

Vilarrasa, V, Bolster, D, Olivella, S & Carrera, J, (2010b). Coupled Hydromechanical Modeling of CO_2 Sequestration in Deep Saline Aquifers. *Int. J. Greenhouse Gas*, 4(6):910-919.

Vilarrasa, V., Olivella, S. & Carrera, J., 2011. Geomechanical stability of the caprock during CO_2 sequestration in deep saline aquifers. *Energy Procedia*, 4: 5306-5313.